NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 2740

EXPERIMENTAL INVESTIGATION OF THE LOCAL AND AVERAGE SKIN FRICTION IN THE LAMINAR BOUNDARY LAYER ON A FLAT PLATE AT A MACH NUMBER OF 2.4

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SUMMARY

Average and local skin-friction coefficients for laminar flow have been determined experimentally on a flat plate at a Mach number of 2.4 for a Reynolds number range of 0.72×10^6 to 2.8×10^6 and compared with the laminar-boundary-layer theory of Chapman and Rubesin.

The average skin-friction coefficients were calculated by the momentum-loss method from impact-pressure surveys of the boundary layer. These coefficients were plotted as a function of Reynolds number based upon distance from the plate leading edge and they were 37 to 94 percent higher than values predicted by theory. This discrepancy is attributed to a momentum loss of unknown origin near the plate leading edge.

Local skin-friction coefficients were determined by evaluating the shear by two methods. In the first method, the shear at the wall was calculated from the measured boundary-layer Mach number gradient at the wall and the measured wall temperature. The mean value of these coefficients was well represented by the theory when the correlation was based on momentum-thickness Reynolds number although the data showed ±20-percent scatter. In the second method, the shear in the boundary layer away from the wall was calculated from the measured Mach number gradient and the theoretical boundary-layer temperature distribution. These shear coefficients showed excellent agreement with the skin-friction coefficient predicted by the theory of Chapman and Rubesin when correlation was based on momentum-thickness Reynolds number.

INTRODUCTION

The results of recent experimental studies of the laminar boundary layer on a flat plate in supersonic flow (references 1 and 2) indicate that the measured average skin-friction coefficients are considerably larger than values predicted by the laminar-boundary-layer theory of Chapman and Rubesin (reference 3). The measured average skin-friction coefficients were determined from the total momentum loss in the boundary layer. The data in reference 1 (Blue) were taken on a flat plate at a Mach number of 2.02 by interferometric and impact-pressure probe measurements in the boundary layer. The average skin-friction coefficients were found to be from 7 to 39 percent higher than the values predicted by laminar-boundary-layer theory. Average skin-friction coefficients, obtained by Higgins and Pappas (reference 2) on a flat plate at a Mach number of 2.4 by impact-pressure probe measurements, were 32 to 48 percent higher than values calculated from the theory.

For flat-plate models, which are only an approximation to a theoretical flat plate, the momentum thickness may not be due to friction effects alone. The theory considers boundary-layer growth on an infinitesimally thick flat plate with zero boundary-layer thickness at the leading edge. The fact that the momentum thickness as measured experimentally differs from that predicted by theory may be attributed to a finite momentum thickness at the plate leading edge and/or a difference in local skin-friction coefficient and/or a difference in the boundary-layer development along the plate surface. Consideration of all these aspects of the problem is necessary to explain adequately the observed high experimental average skin-friction coefficients.

An insight to the problem is provided by Bradfield (reference 4), who measured average skin-friction coefficients in the laminar boundary layer of a 15° cone at a Mach number of 3.1. These experimental data checked the values predicted by the laminar-boundary-layer theory for flat plates when the theoretical relation between conical flow and flat-plate flow was considered. The agreement between the theory and the data of Bradfield substantiates the theory where the actual flow boundary conditions are essentially those postulated in the theory. That is, the leading-edge effects on the cone data should be negligible due to the nature of the cone geometry and the symmetry of the shock wave.

The discrepancy between the flat-plate data and the theoretical values of average skin friction might be eliminated if local values of skin friction were measured and correlated with Reynolds number based on boundary-layer momentum thickness. This would eliminate the effects of the plate leading edge provided the boundary-layer growth along the plate, after the initial build-up at the leading edge, corresponded to boundary-layer growth predicted by theory.

It is the purpose of this report to present experimental data on local and average skin friction and to compare these data with the results given by laminar-boundary-layer theory.

NOTATION

a	speed of sound, feet per second
c_f	local skin-friction coefficient $\left(\frac{\tau_w}{1/2\ \rho_o u_o^2}\right)$, dimensionless
C_f	average skin-friction coefficient $\left(\frac{1}{x}\int_0^x c_f dx\right)$, dimensionless
c_p	specific heat at constant pressure, Btu per pound, °F
g	gravitational constant (32.2), feet per second squared
k	thermal conductivity, Btu per second, square foot, °F per foot
M	Mach number, dimensionless
Pr	Prandtl number $\left(\frac{\mu c_p g}{k}\right)$, dimensionless
Re	Reynolds number $\left(\frac{u_o \rho_o x}{\mu_o}\right)$, dimensionless
Re_θ	momentum-thickness Reynolds number $\left(\frac{u_o \rho_o \theta}{\mu_o}\right)$, dimensionless
T	temperature, °F absolute
u	velocity parallel to plate, feet per second
x	distance along plate from leading edge, feet
y	distance normal to plate, feet
γ	ratio of specific heats, 1.40 for air, dimensionless
δ	boundary-layer thickness, feet
θ	momentum thickness, feet
μ	viscosity, pound-second per square foot
ν	kinematic viscosity $\left(\frac{\mu}{\rho}\right)$, square feet per second
ρ	mass density, slugs per cubic foot
τ	local shear stress, pounds per square foot

Subscripts

o free-stream conditions

w plate-surface conditions

DESCRIPTION OF EQUIPMENT

Ames 6-Inch Heat-Transfer Tunnel

The 6-inch heat-transfer tunnel used for the tests has been described in detail in reference 5.

The Flat-Plate Model

The flat-plate model used for the tests, shown schematically in figure 1, was constructed of masonite diestock and copper. The test model was 22.38 inches long, 5.49 inches wide, and 0.63 inch thick. The forward 12.38 inches of the model was constructed of copper with suitable internal ducting to provide passages for the heating or cooling fluid. The 10-inch masonite-diestock tailpiece of the model was bolted to the tunnel walls to support the model. The copper section of the model was bolted to the tunnel wall which supported the external ducting for the fluid passage. The leading edge of the flat plate was chamfered to form an angle of 10° and was rounded to a radius of about 0.005 inch to avoid feathering. The top surface and the bottom 10° leading-edge surface of the copper were chromium-plated, and the top chromium surface was ground and polished until the average surface roughness, as measured with a profilometer, was less than 10 microinches. The model spanned the tunnel and was sealed at the walls.

Ten thermocouples, made from calibrated iron and constantan wires, were peened into the underside of the top surface of the plate. The thermocouples were spaced at 1-inch intervals along the plate center line starting from the plate leading edge, and they indicated temperatures one-sixteenth inch below the plate surface.

Eight static-pressure orifices, 0.0135 inch in diameter, were alternately spaced, 1 inch apart streamwise, on two lines located 1.63 inches from each side of the plate. The first orifice was located 2 inches from the plate leading edge.

Boundary-Layer Survey Apparatus

An impact-pressure survey apparatus was mounted above and downstream of the flat-plate model so that impact-pressure surveys could be made in the boundary layer at the desired test conditions. The impact-pressure probe (see fig. 1) was constructed of flattened hypodermic tubing, and had a rectangular opening 0.080-inch by 0.009-inch outside dimensions and 0.075-inch by 0.004-inch inside dimensions. With the probe in contact with the plate, the center line of the probe was 0.0045 inch above the plate surface.

Cooling and Heating System

The system for raising and lowering the temperature of the plate surface was as follows: An ethylene glycol-water mixture was forced through the ducting in the test model by a small circulating pump. For lowering the plate temperature, the glycol-water mixture was cooled by passing it through a Freon refrigerating unit, and the plate temperature level was adjusted by a thermostatically controlled mixing valve. For raising the temperature of the model, the glycol-water mixture was passed through a 4-kilowatt calrod immersion heater, and the plate temperature level was adjusted by a variable-voltage transformer which controlled the electrical input to the heater.

TEST PROCEDURE AND REDUCTION OF DATA

Range of Test Conditions

The tests were conducted at a nominal Mach number of 2.4. The region from 1 inch to 6 inches from the plate leading edge constituted the testing region. The tunnel stagnation pressure was varied from 8 to 25 pounds per square inch absolute. The corresponding Reynolds number range, evaluated from free-stream properties of the air flow, was from 0.72×10^6 to 2.8×10^6.

The temperature of the plate surface was varied from -12° F to 230° F, and the corresponding ratio of surface temperature to free-stream temperature (T_w/T_o) was 1.59 to 2.76. The recovery temperature ratio (T_w/T_o), for the case of no heat transfer, was 2.02. The present tests were conducted in conjunction with experiments to determine the effect of heating and cooling the surface of a flat plate on boundary-layer transition. Mach number profiles were taken in the laminar region of the boundary layer for each of the above-mentioned temperature levels, and these results were evaluated to obtain skin-friction data.

Method of Obtaining Data

The static and impact pressures were obtained from the orifices in the plate surface and the impact-pressure probe, respectively. These pressures were used to determine the free-stream Mach number and the local Mach numbers in the boundary layer. The impact and static pressures were measured on a dibutyl-phthalate manometer with a high vacuum as a reference. The reference pressures were measured with a McLeod gage.

In making the boundary-layer surveys with the impact-pressure probe, the height of the probe above the plate surface was measured with a dial indicator mounted on a cathetometer. The least count of the indicator was 0.0001 inch. The telescope of the cathetometer was sighted through one test-section window on a line scribed on the probe. The zero distance of the probe above the plate was determined by visual means. It is believed that the relative position of the probe above the plate surface could be measured to ±0.001 inch.

The time lag to obtain an impact-pressure measurement varied with the absolute pressure measured and was on the order of 5 to 15 minutes. A pressure time history was made for each impact-pressure reading during the surveys to establish the steady-state values.

The plate-surface temperature and the wind-tunnel stagnation-air-temperature thermocouple voltages were recorded for each run with a manual-balancing laboratory potentiometer.

Reduction of Data

The momentum thickness is defined as

$$\theta = \int_0^\delta \frac{\rho u}{\rho_o u_o}\left(1 - \frac{u}{u_o}\right) dy \tag{1}$$

This equation when expressed in terms of free-stream Mach number, local temperature in the boundary layer, and local Mach number in the boundary layer, becomes

$$\theta = \frac{1}{M_o^2}\int_0^\delta \left[MM_o\left(\frac{T_o}{T}\right)^{1/2} - M^2\right] dy \tag{2}$$

The theory of Crocco (reference 6), which is based on the assumption that Prandtl number is unity, gives an expression for the temperature distribution through the boundary layer with heat transfer. This equation, when expressed in terms of Mach number and temperature, becomes

$$T^{1/2} = \frac{\left[\left(1 + \frac{\gamma-1}{2} M_o^2\right)\frac{T_o}{T_w} - 1\right]\frac{M}{M_o}\frac{T_w}{T_o^{1/2}}}{2\left(1 + \frac{\gamma-1}{2} M^2\right)} +$$

$$\frac{\left\{\left[\left(1 + \frac{\gamma-1}{2} M_o^2\right)\frac{T_o}{T_w} - 1\right]^2 \frac{M^2}{M_o^2}\frac{T_w^2}{T_o} + 4\left(1 + \frac{\gamma-1}{2} M^2\right) T_w\right\}^{1/2}}{2\left(1 + \frac{\gamma-1}{2} M^2\right)} \tag{3a}$$

For the case of no heat transfer, equation (3a) reduces to

$$\frac{T}{T_o} = \frac{1 + \frac{\gamma-1}{2} M_o^2}{1 + \frac{\gamma-1}{2} M^2} \tag{3b}$$

The temperature distribution in the boundary layer was calculated from the measured Mach number profiles and measured plate temperatures using equation (3a) or (3b). The momentum thickness was calculated for each test condition by integrating equation (2) numerically, using Simpson's rule from the above-calculated temperature profiles and the experimental Mach number boundary-layer profiles.

The average skin-friction coefficients for each test condition were evaluated from the equation defining the momentum decrement for flat-plate flow.

$$C_f = 2\theta/x \tag{4}$$

The local skin-friction coefficients were determined in the following manner: The shear stress in a laminar boundary layer is given by

$$\tau = \mu\frac{\partial u}{\partial y} \tag{5}$$

By expressing equation (5) in terms of Mach number, speed of sound, and temperature, the local shear stress can be represented in coefficient form by

$$\frac{\tau}{1/2\ \rho_o u_o^2} = \frac{2\mu a}{\rho_o u_o^2}\left(\frac{M}{2T}\frac{\partial T}{\partial y} + \frac{\partial M}{\partial y}\right) \tag{6a}$$

For evaluating the shear at the wall, equation (6a) reduces to

$$c_f = \frac{2\mu_w a_w}{\rho_o u_o^2}\left(\frac{\partial M}{\partial y}\right)_w \tag{6b}$$

Two methods of evaluating local skin-friction coefficients were employed. The first method was to evaluate the shear at the wall using equation (6b). The Mach number gradient at the wall was determined graphically from the faired curves of the Mach number distribution in the boundary layer. The viscosity and the speed of sound were evaluated at the measured wall temperature. The local skin-friction coefficients evaluated in this manner from the present data included test conditions of heat transfer to and from the plate surface and also no heat transfer.

The second method of determining the local skin-friction coefficients from the experimental data was to evaluate the shear away from the wall, using equation (6a). The theoretical results of Young and Janssen (reference 7) show that the shear stress decreases only 3 percent from the wall to a point 30 percent of the boundary-layer thickness away from the wall. Thus, local shear could be obtained away from the wall to represent the skin-friction coefficient with reasonable accuracy. At a selected distance away from the wall, the Mach number and the Mach number gradient were obtained from the faired curve of the experimental Mach number distribution. The associated local temperature and the local temperature gradient in the boundary layer were calculated from the theory of reference 3 (Chapman and Rubesin) for each profile corresponding to the experimental momentum thickness.[1] The properties, viscosity and speed of sound, were evaluated at the local temperature. Values of the skin-friction coefficients were determined at two different y positions within the inner 30 percent of the boundary-layer thickness as a check on the accuracy of this method. This method was used to evaluate only the data taken at adiabatic wall temperature.

Discussion of Experimental Errors

A maximum variation of 1 percent in free-stream Mach number existed along the testing region as evidenced in figure 2. The effect of this Mach number variation on the average skin-friction coefficients would introduce an error of less than 1 percent in the measured value of C_F.

The error in determining the local skin-friction coefficients at the wall is directly proportional to the error in determining the Mach number gradient at the wall. The region of the boundary layer immediately adjacent to the wall cannot be well defined by impact-pressure measurements since the presence of the finite-size probe near the surface alters

[1] The theory of Chapman and Rubesin ($Pr = 0.72$) more closely approximates the temperature distribution for the adiabatic case than Crocco's theory ($Pr = 1$). However, Crocco's theory was more convenient to use for determining the boundary-layer momentum thickness, especially when there was heat transfer. Values of momentum thickness calculated using Crocco's theory were approximately 1 percent lower than values calculated using the Chapman and Rubesin theory.

the flow, and may give incorrect readings of the true flow conditions. Thus, the faired curves of the Mach number in the boundary layer subject the graphical determination of $(\partial M/\partial y)_w$ to a source of error. The maximum scatter of ±20 percent in the local skin-friction coefficients obtained in the above manner can be largely attributed to the error in determining $(\partial M/\partial y)_w$.

In determining the shear in the region of the boundary layer approximately 30 percent of the boundary-layer thickness away from the wall, $\partial M/\partial y$ could be determined more accurately because of the approximate linear variation of Mach number with y and because the Mach number could be accurately measured in this region. Local skin-friction coefficients were determined from shear measurements in the region from 22 to 30 percent of the boundary-layer thickness away from the wall. The average difference in two separate evaluations was less than 3 percent, with the value of the skin-friction coefficient farther out in the boundary layer always being smaller, as predicted by theory. A possibility of additional error could have been introduced since a theoretical temperature distribution through the boundary layer (see reference 3) was used to evaluate c_f from equation (6a). However, since the temperature term in equation (6a) contributes less than 1 percent of the total value of c_f, any error introduced by this term could be disregarded. A maximum error of 2 percent could be introduced in evaluating the local value of μa in equation (6a), when the theoretical temperature distribution through the boundary layer was used.

RESULTS AND DISCUSSION

Typical temperature distributions along the flat-plate model for the various nominal plate temperature levels are shown in figure 3. The adiabatic wall-temperature variation along the insulated plate is within $\pm 1^\circ$ F. For the cases with heat transfer, the plate temperature is substantially constant over the region from $x = 3.5$ inches to $x = 10$ inches. There is a decided temperature gradient from the leading edge of the plate back to $x = 3.5$ inches for the heated and cooled runs, but since the laminar theory predicts a small change in average skin-friction coefficient for a considerable change in wall temperature along the plate, the effect of the variable wall temperature can be neglected. The maximum effect of the measured variable wall temperature on the average skin-friction coefficient would be approximately 1 percent. There is no effect of the variable wall temperature on the local skin-friction coefficient as it was determined in these tests from the experimentally determined shear at the wall.

Typical Mach number profiles for the laminar boundary layer are shown in figure 4 for an x position of 6 inches. The range of nominal wall temperatures was from -12° F to 230° F, and the Reynolds number range was from 0.97×10^6 to 2.81×10^6. These profiles are clearly laminar in shape. It should be noted that the measured Mach number nearest the wall for each profile is a high value as compared to the faired curve. This point was disregarded when fairing the curves into the zero reading at the wall because the wall and impact-tube interference contributes to a false pressure reading at this position. Mach number distributions in the laminar boundary layer were obtained for x positions of 1, 2, 3, 3.5, 4, 5, and 6 inches and plotted in the manner as shown in figure 4 to determine the local and average skin-friction coefficients.

The average skin-friction data are compared with the laminar-boundary-layer theory of Chapman and Rubesin in figure 5. This comparison is made in terms of Reynolds number based upon length of run of the boundary layer. These data are between 37 and 94 percent higher than values predicted by theory. This discrepancy is of the same order of magnitude as that found in references 1 and 2.

A comparison of the measured momentum thickness with the momentum thickness of the laminar boundary layer as predicted by theory is presented in figure 6. These measurements were made at a tunnel stagnation pressure of 18 psia at the x positions indicated in figure 6. The measured momentum thicknesses are 61 to 94 percent higher than values predicted by the theory. The boundary-layer growth along the plate after $x = 1$ inch appears to be similar to the growth indicated by the theory. Apparently, there is some effect near the leading edge that contributes a large momentum loss to the boundary layer which increases the measured momentum thickness above that predicted by theory.

The local skin-friction coefficients for the laminar boundary layer that are presented in figure 7, as a function of Reynolds number based on momentum thickness, were evaluated by determining the shear at the wall from the measured Mach number gradient and temperature at the wall. These local skin-friction coefficients were evaluated from the boundary-layer Mach number profiles that were used in the evaluation of the average skin-friction data shown in figure 5. The data correlate within ±20-percent scatter and the mean of the data is well represented by the theoretical curve. This scatter for the most part can be attributed to the uncertainty of measuring the Mach number gradient at the wall.

The local skin-friction data that were obtained at adiabatic wall temperature by the first method again are compared with theory in figure 8. These data will be used to compare the relative accuracy of the two methods of determining the local shear.

In the second method, the shear in the boundary layer away from the wall was calculated from the measured Mach number gradient in the boundary layer and the theoretical temperature distribution. These results, which are compared with the theory in figure 9, are more consistent with the theory and show considerably less scatter than the data in figure 8. Local skin-friction coefficients were evaluated at two points in the boundary layer away from the wall for each boundary-layer profile, and these two values are shown in figure 9 for each value of Re_θ. The lower value at each Re_θ corresponds to that calculated for the greater distance away from the wall. Since the theory for adiabatic wall temperature predicts that the shear decreases in the direction away from the wall, these lower values of local skin friction are consistent with theory.

A comparison is made in figure 10 of a typical measured boundary-layer Mach number profile with the profile calculated from the theory of Chapman and Rubesin based upon equivalent momentum thickness Reynolds number. The experimental data are well represented by the theoretical curve.

Since the measured values of the local skin-friction coefficient agree with theory when correlation is based on momentum-thickness Reynolds number, and since the experimental average skin-friction coefficients, as determined from momentum-loss measurements, are greater than the theoretical values, it can be concluded that the high indicated momentum loss can be attributed to effects near the plate leading edge. Moreover, since the experimental Mach number distributions as well as the local values of skin-friction coefficients agree well with the theoretical values when correlation is based on momentum-thickness Reynolds number, it follows that the boundary-layer growth should be similar to that predicted by theory downstream of initial momentum loss near the leading edge. This similarity in boundary-layer growth is evidenced in figure 6.

Thus, these data, together with the average skin-friction-coefficient data taken by Bradfield (reference 4) tend to verify the validity of the laminar-boundary-layer theory of Chapman and Rubesin. However, further experimental investigations are required to explain the leading-edge effects of flat plates (and other bodies) on the growth of the laminar boundary layer.

CONCLUDING REMARKS

The experimental average skin-friction coefficients presented here are from 37 to 94 percent higher than values calculated from the theory of Chapman and Rubesin when the results are plotted as a function of Reynolds number based on distance from the plate leading edge. This discrepancy can be attributed to a momentum loss of unknown origin near the plate leading edge.

Local skin-friction coefficients were evaluated by two separate methods. The first consisted of determining the shear at the wall from the measured Mach number gradient and the wall temperature. The second consisted of approximating the skin friction by determining the shear in the boundary layer away from the wall from the experimental Mach number gradient and the corresponding theoretical temperature and temperature gradient. The second method of obtaining the skin-friction coefficients yielded much more consistent results than the first method.

The experimental variation of the local skin-friction coefficient with momentum-thickness Reynolds number is adequately represented by the Chapman and Rubesin theory within the range of these tests.

Ames Aeronautical Laboratory
National Advisory Committee for Aeronautics
Moffett Field, Calif., May 12, 1952

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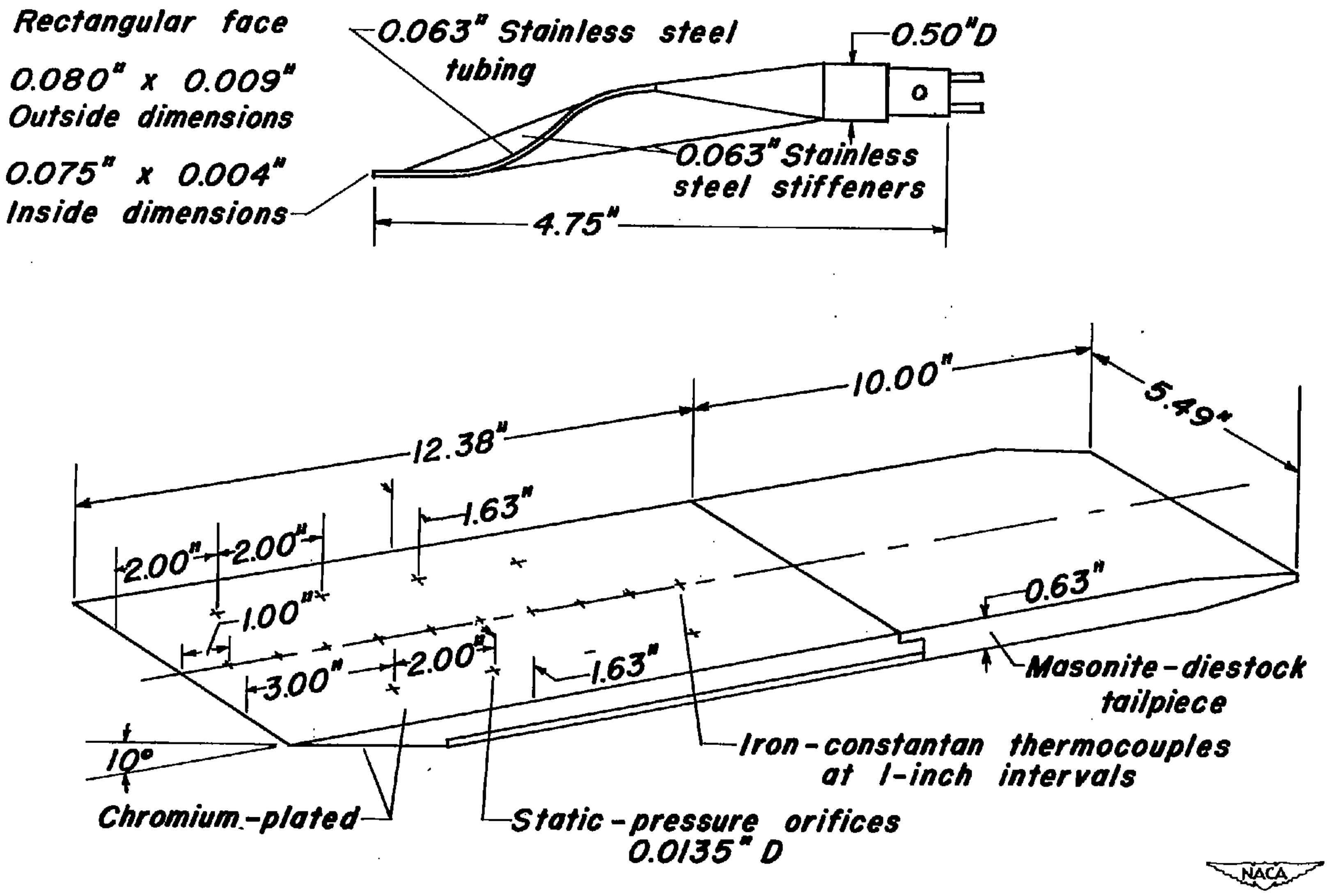

Figure 1. — Sketch of flat-plate copper model and impact-pressure probe.

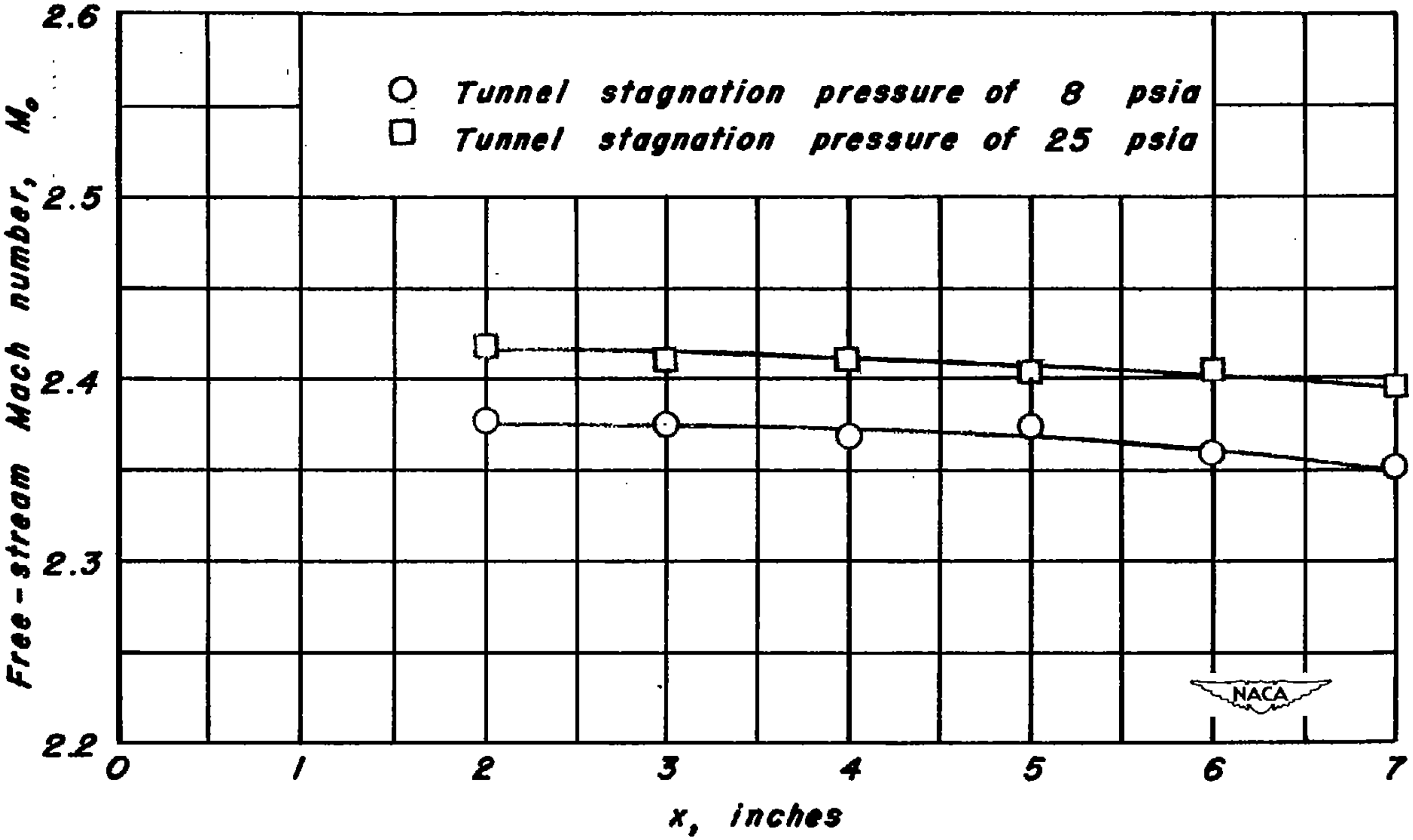

Figure 2.— Mach number distribution along the flat-plate model.

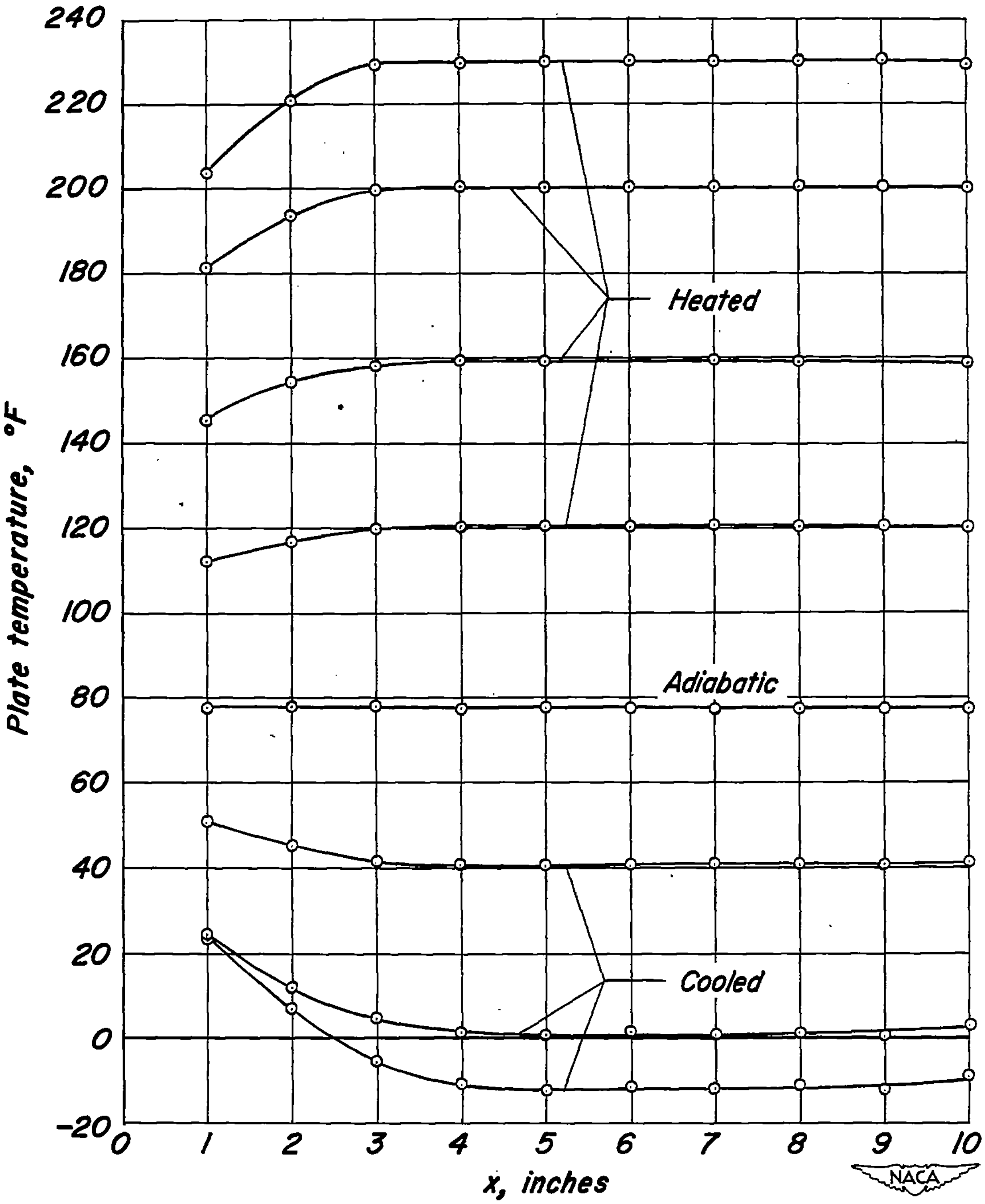

Figure 3.— Typical temperature distributions along the flat-plate model with laminar-boundary-layer flow.

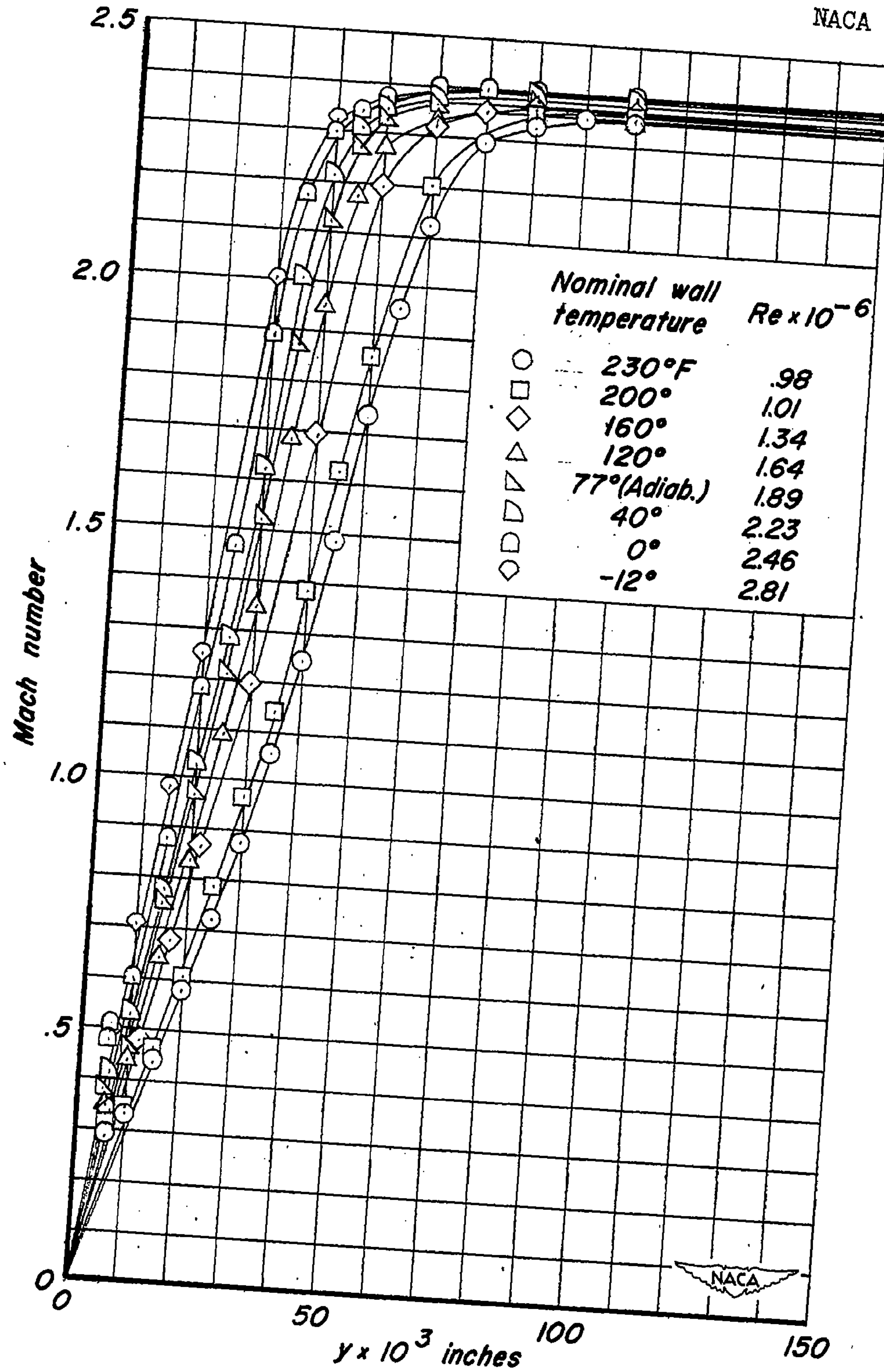

Figure 4.– Typical Mach number profiles for the laminar boundary layer at $x = 6$ inches.

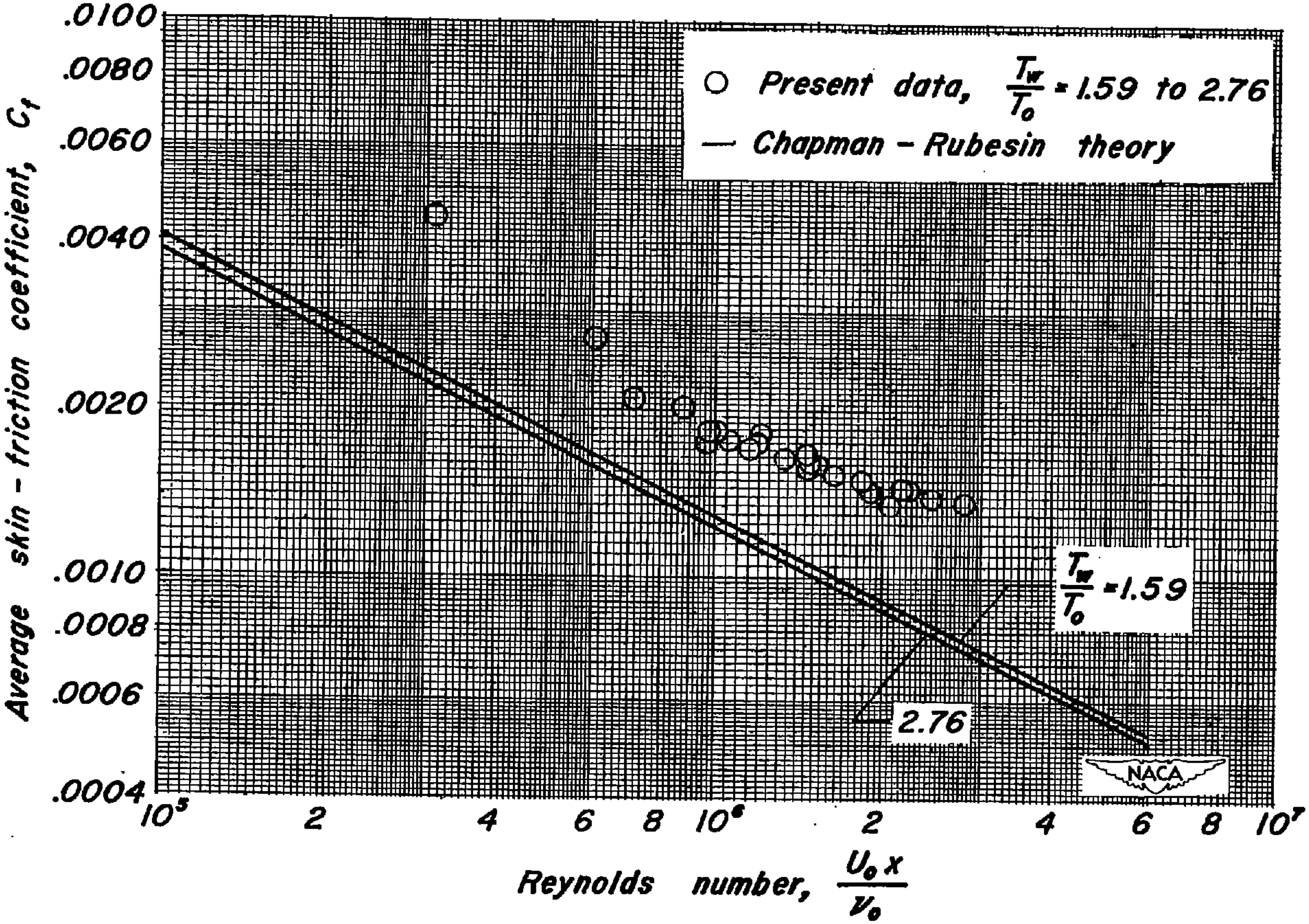

Figure 5. – Average skin-friction coefficients of the laminar boundary layer on the flat-plate model at $M = 2.4$.

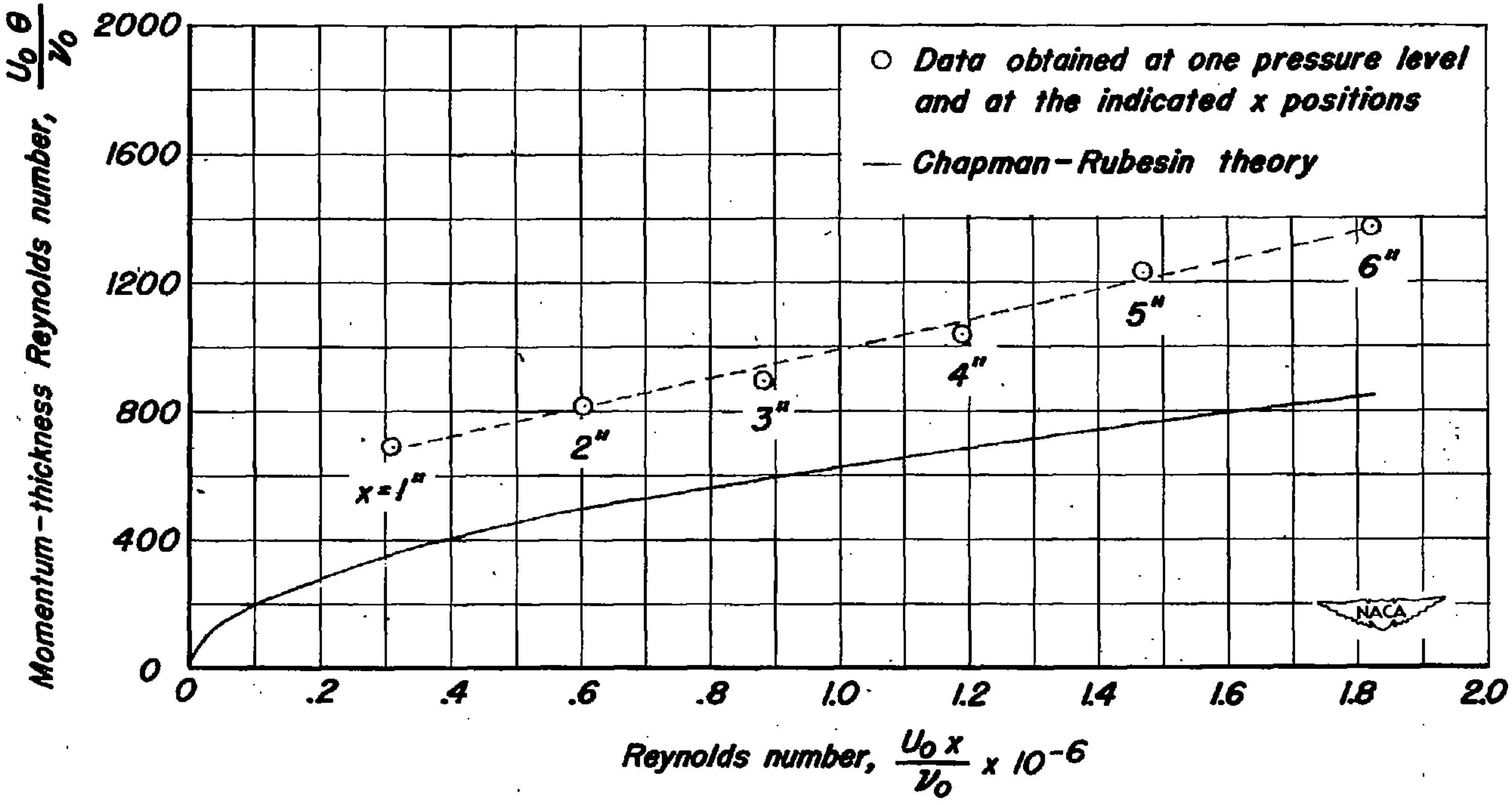

Figure 6.—Variation of momentum thickness along the flat-plate model for laminar-boundary-layer flow.

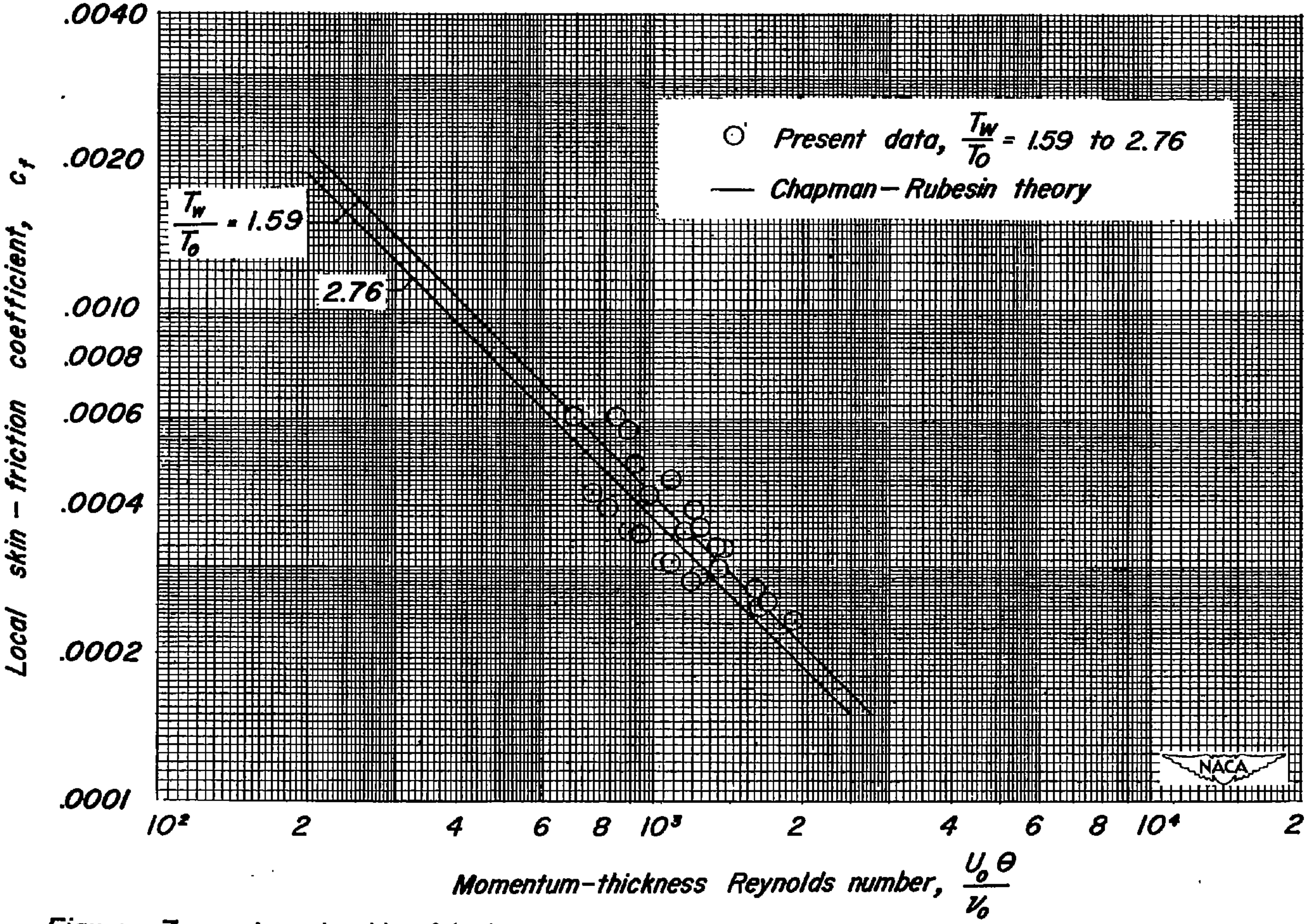

Figure 7. — Local skin-friction coefficients determined from shear at the wall.

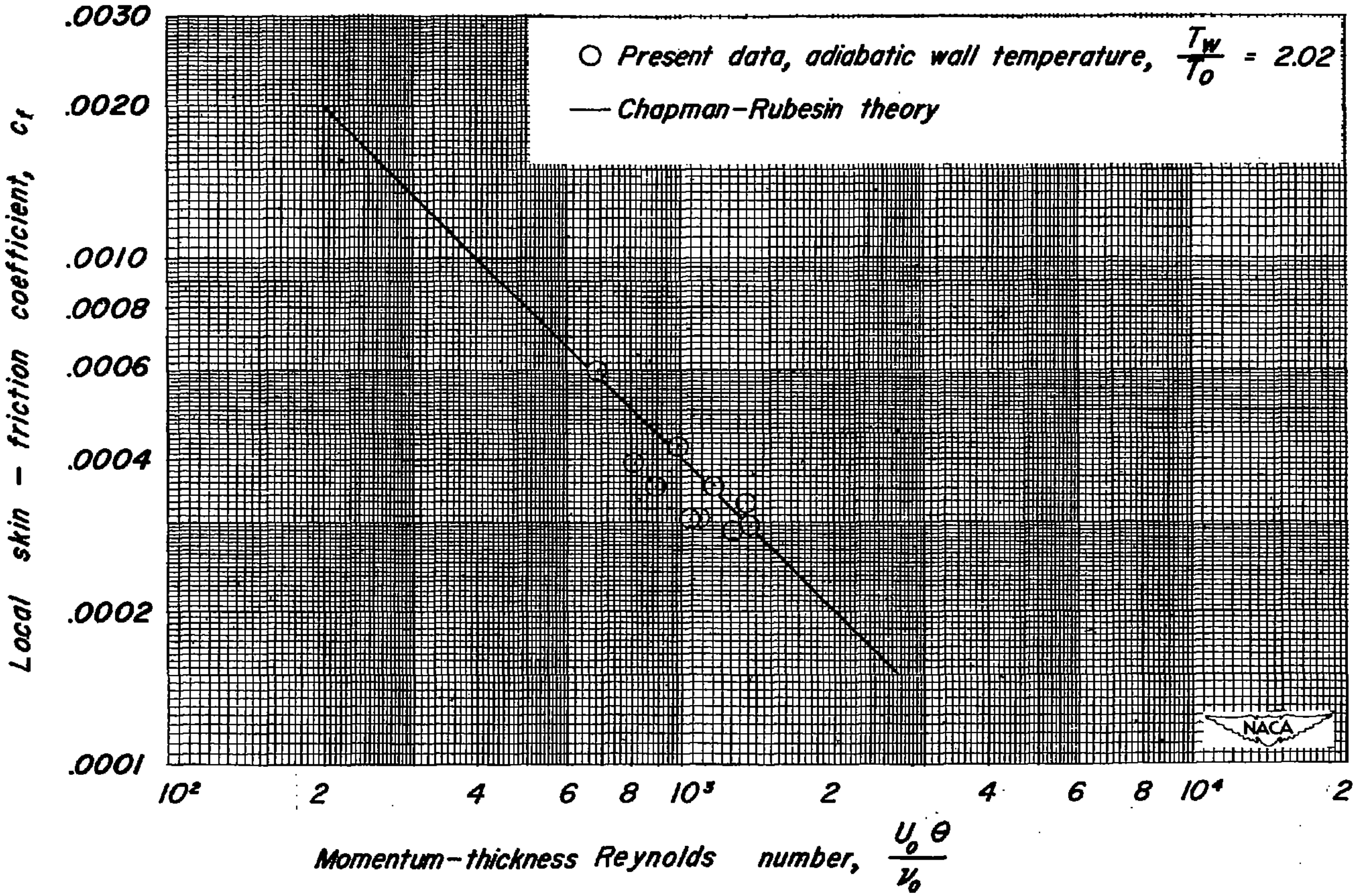

Figure 8. — Local skin-friction coefficients determined from shear at the wall.

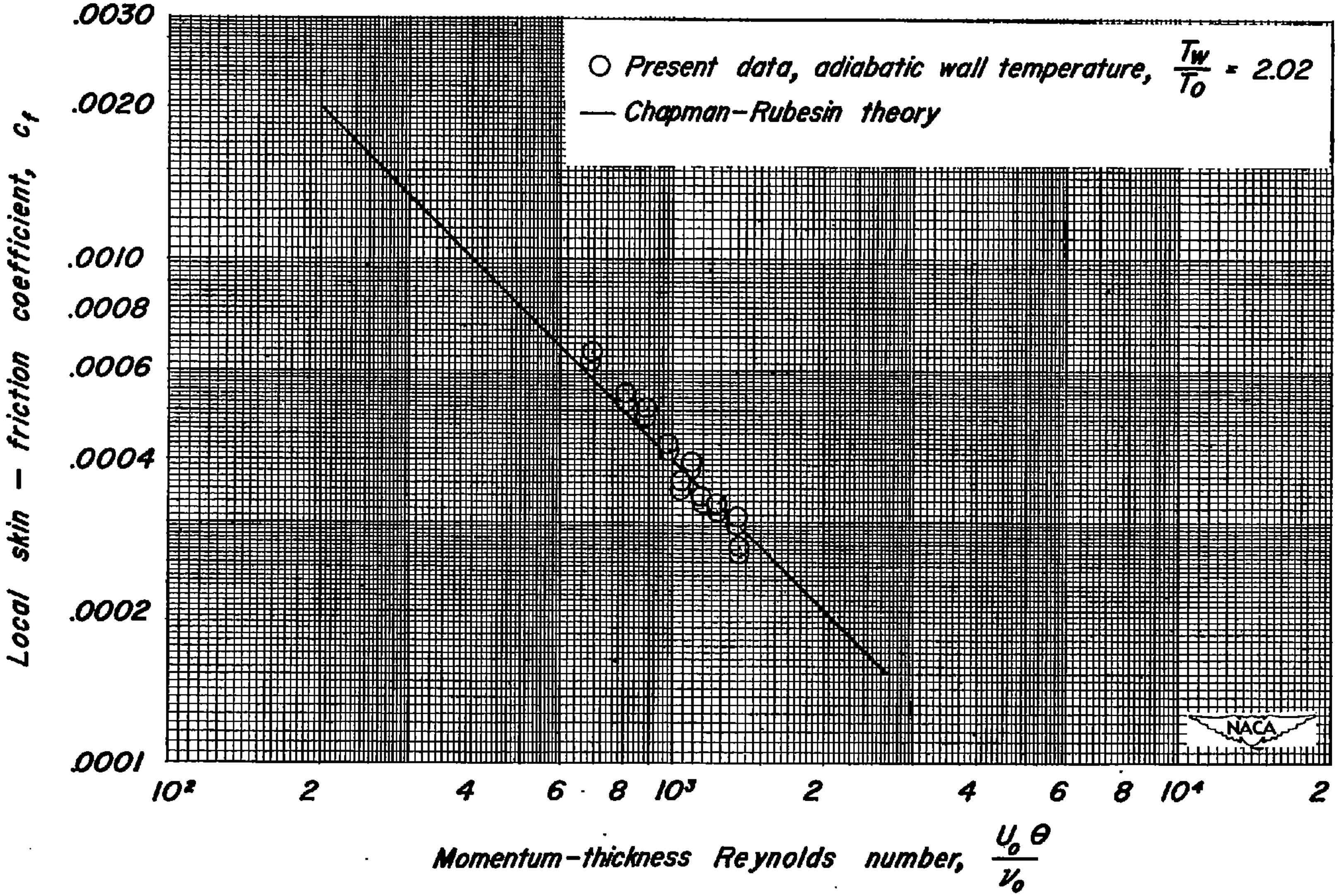

Figure 9. — Local skin - friction coefficients determined from local shear away from the wall.

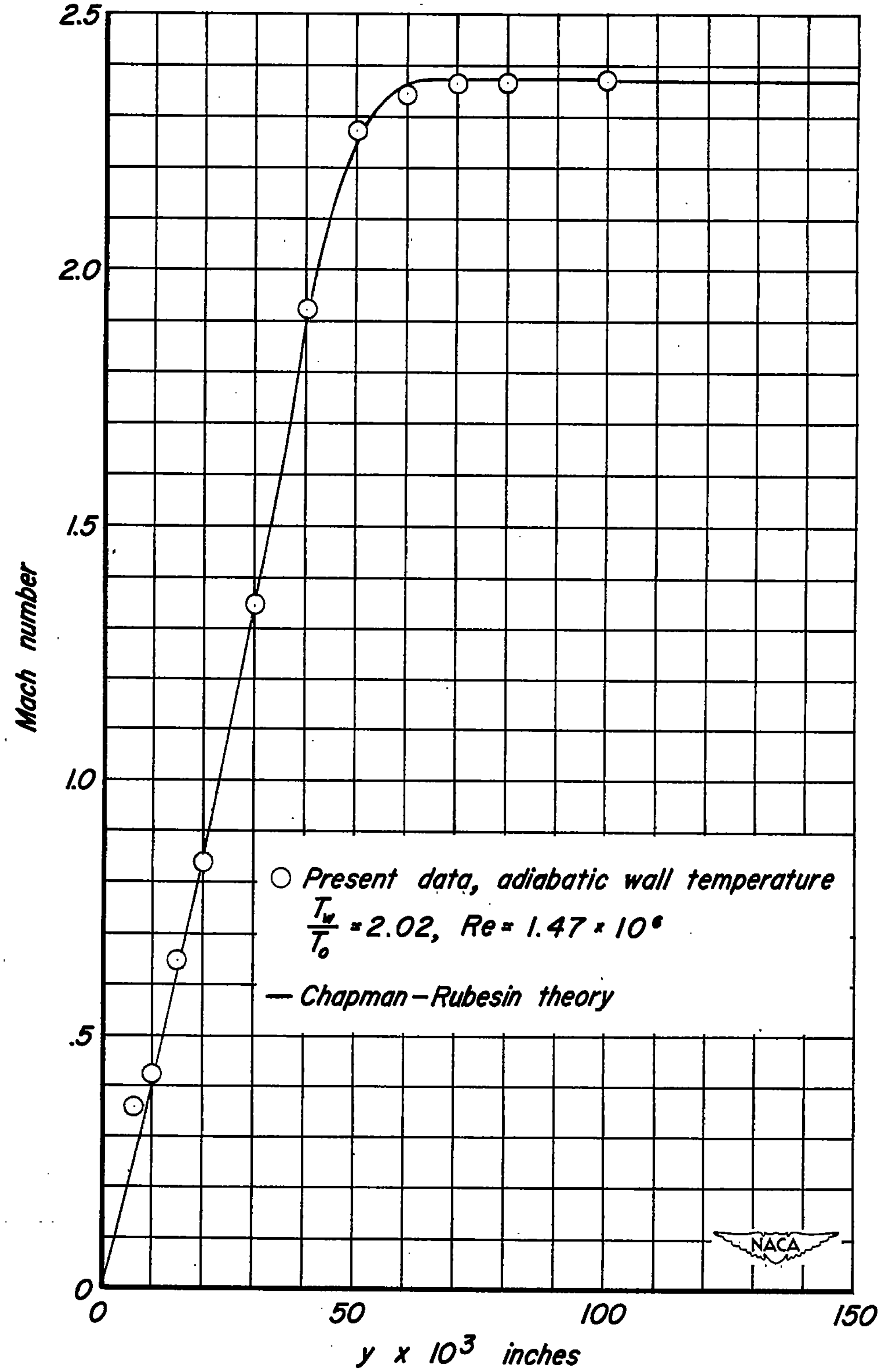

Figure 10.— Comparison of theoretical and a typical experimental Mach number boundary-layer profile, x = 6 inches.